RU-96-06
hep-ph/969602334

Signatures for Squarks in the Light Gaugino Scenario

Glennys R. Farrar[1]

Department of Physics and Astronomy
Rutgers University, Piscataway, NJ 08855, USA

Abstract: When the gluino is light and long lived, missing energy is a poor signature for both squarks and gluinos. Instead, squark pair production leads to events with ≥ 4 jets. If a chargino can decay to squark and quark, missing energy is also a poor signature for the chargino. Properties of 4-jet events originating from squarks are discussed. ALEPH's preliminary report of an excess of 4-jet events, with a peak in total dijet mass of 109 GeV, is analyzed in terms of $S_q S_q^*$ and chargino pair production.

[1]Research supported in part by NSF-PHY-94-23002

Motivations are accumulating for believing the gluino and photino may be light. This is inevitable as long as SUSY-breaking does not arise from gauge singlet vevs and is transmitted to ordinary particles by exchange of very heavy states. In this case gaugino masses and other dimension-3 SUSY-breaking operators are suppressed by a factor M^{-1} compared to squark masses and other dimension-2 SUSY-breaking operators. This has a number of attractive concomittants:

- There is no SUSY CP problem[1].
- Gluino and photino masses are calculable in terms of μ, $tan\beta$, and squark and Higgs masses. Given constraints on these parameters, gluino and photino masses are $\leq O(1)$ GeV. The mass of the lightest gluino-containing hadron (the gluino-gluon bound state called R^0) is $\sim 1.3 - 2.2$ GeV[1]. A chargino is lighter than the W[2].
- With these R^0 and photino masses, the photino relic density is naturally of the correct order of magnitude to account for the dark matter of the universe[3].
- The R^0 lifetime $\tau(R^0) \gtrsim (10^{-7} - 10^{-10})(\frac{M_{sq}}{100\mathrm{GeV}})^4$ sec[1] is long enough that it is unlikely to have been detected in existing searches[4].
- An "extra" pseudoscalar is predicted in the flavor singlet meson spectrum at $\sim 1\frac{1}{2}$ GeV; such a state has been observed[4, 5].
- The ground state R-baryon ($uds\tilde{g}$) may be stable and provide an explanation for cosmic ray events with energies in excess of the GZK bound[6] and anomalous Cygnus X-3 events[1].

In earlier papers I have discussed the phenomenology of light R-hadrons and strategies for detecting them. Here I focus on the modifications of the squark

[2]Unless $\mu \gtrsim$ few TeV[2].

signature which this scenario implies, as well as the consequent modifications to chargino signatures if these can decay to a squark.

Aside from having spin-0 and larger mass, squarks are produced much like quarks. Once produced, squarks decay dominantly via $S_q \rightarrow q + \tilde{g}$. The gluino hadronizes forming a jet, due to the long lifetime of the R^0. This is to be contrasted with the conventional case of a very heavy and thus short lived gluino, for which the photino production is prompt and missing energy is a good signature[7]. When the R^0 in the gluino jet finally decays, the energy carried by the photino is so small that the conventional missing energy signature is not useful[8]. Existing collider limits do not apply[3].

In prinicple, squarks can be reconstructed by pairing jets. However experience with $W \rightarrow q\bar{q}$ and $t \rightarrow bq\bar{q}$ shows that at a hadron collider further constraints will be necessary to reduce QCD background. The remainder of this paper is devoted to establishing a search procedure for squarks when their predominant decay is to two or more jets.

Squarks with masses almost $\frac{1}{2}E_{cm}$ can be pair produced in e^+e^- collisions. In a hadron collider they can be produced either in pairs from $q\bar{q}$ annihilation and gluon-gluon fusion, or singly in association with a gluino or (at the $\sim 1\%$ level) a photino. At an e^-p collider they are produced singly in association with a gluino or photino. Pair produced squarks generate events containing four or more jets.

At an e^+e^- collider, the search for squarks may be complicated by the presence of an indirect source of squarks which is potentially even more important than the direct production, namely cascade production from pair produced charginos. When gaugino masses vanish at tree level, the mass of the lighter chargino is less than M_W: $m(\chi^{\pm}) = (\sqrt{\mu^2 + 4M_W^2 sin2\beta} - |\mu|)/2$.

[3]Squarks decay directly to a photino and quark with a branching fraction $Q_{sq}^2\alpha_{em}/(\frac{4}{3}\alpha_s)$. Rescaling the UA(1) and Tevatron collider limits to account for this factor 100 loss in sensitivity, produces limits inferior to those discussed below from the Z^0 hadronic width.

If a L-squark (say S_{uL}) or the R-stop is lighter than the chargino, major chargino decay modes will be: $\chi^+ \to S_{uL}\bar{d}_L$, $\chi^+ \to S_{tR}\bar{b}_L$, etc. Above threshold, chargino pairs are copiously produced in e^+e^- collisions so the cascade chain $e^+e^- \to \chi^+\chi^-$, followed by $\chi^\pm \to S_q q'$ can be the dominant source of squarks. Note that the best chargino mass limits rely on a missing energy signature. When the branching fraction to such states is reduced by competition from $\chi^\pm \to S_q q'$ the limits on chargino masses are impaired.

The best limit on squark masses prior to LEP running at 130 GeV, if missing energy is not useful, comes from the determination of the hadronic width of the Z^0. Neglecting quark masses, $\sigma(e^+e^- \to S_q S_q^*) = \frac{1}{2}\beta^3\sigma(e^+e^- \to q\bar{q})$ for any given flavor and chirality[4]. Therefore production of a $(u_L,\ u_R,\ d_L,\ d_R)$-type pair would increase the total hadronic width of the Z^0 by a fraction $(0.06,\ 0.01,\ 0.09,\ 0.003)\beta^3$. The limit on "extra" hadronic width of the Z^0 then limits the mass of squarks. If there are four or more degenerate "light" squarks, their mass must be greater than $\sim M_Z/2$. If only a single flavor of squark is light, this limit is greatly reduced, to $\lesssim 30$ GeV for a L-chiral squark. Masses of R-chiral squarks are comparatively unconstrained due to their weak coupling to the Z^0. Considering $e^+e^- \to S_q\bar{q}\tilde{g} + S_q^* q\tilde{g}$ and virtual corrections to $e^+e^- \to q\bar{q}$ allows the degenerate squark limit to be improved to $50-60$ GeV[9, 10]. The analysis should be redone with new Z^0 width values and using $\alpha_s(Q)$ determined assuming a light gluino; the limit should be given as a function of the number of light squarks of each flavor and chirality.

Consistency between the observed top mass and its rate in conventional signatures limits the stop mass to slightly less than the top mass since otherwise $t \to S_t + \tilde{g}$ would be the top's main decay mode. Limits on isospin-violating radiative corrections to precisely measured electroweak parameters can be used to constrain the sbottom-stop splitting, as was done long ago in

[4]Although squarks have spin-0, they can be ascribed chirality because supersymmetry associates them with a quark of definite chirality and chirality mixing is small for the superpartners of light-quarks.

[11] in a particular model.

In the recent LEP run at $E_{cm} = 130-136$ GeV, ALEPH[5] found 14 events which meet their 4-jet criteria, when 7.1 events are expected from standard model physics and less than one 4-jet event is expected from either hA or H^+H^- production. Furthermore, 8 of these 4-jet events have a total dijet mass of $\sim$ 109 GeV. Approximating the statistical error associated with 7 events by $\pm\sqrt{7}$, the ALEPH data gives $R_{\geq 4} = 2.0 \pm 0.4$. If the 7 event excess is averaged over all four LEP experiments, assuming equal sensitivity and no excess in other experiments, $R_{\geq 4} = 1.25 \pm 0.1$. Let us now see whether such events have a natural interpretation in terms of squark production. Even if the ALEPH excess proves ephemeral, the discussion below provides a vehicle for indicating the types of constraints which can be brought to bear in every squark search. We start with the possibility of direct $S_q S_q^*$ production and then turn to production via chargino cascade.

The most striking feature of squark pair production is the excess number of events with 4 or more jets. To be more quantitative, define $f_{\geq 4}$ to be the fraction of ordinary events with four or more jets, for a given energy and jet-finding algorithm. In ALEPH's analysis, $f_{\geq 4} = 0.1$. For each flavor i define $r_i(m_i, E) \equiv (\sigma(e^+e^- \rightarrow S_q^i S_q^{i*}))/(\Sigma_i\ \sigma(e^+e^- \rightarrow q^i \bar{q}^i))$. Denote the ratio of the actual number of $n_{jet} \geq 4$ events to the number expected in the standard model by $R_{\geq 4}(E)$. If the only source of events with $\geq$ 4 jets are standard model processes and $S_q S_q^*$ production, $R_{\geq 4}(E) = \frac{\Sigma_i\ r_i(m_i,E)+f_{\geq 4}}{f_{\geq 4}}$. Fig. 1 shows $R_{\geq 4}(m, E)$ for $E = 133$ and 190 GeV in the illustrative case (called dls) that $u,\ d,\ s,\ c$ squarks are degenerate. A LEP measurement of $R_{\geq 4} = 1.25 - 2.4$ at $E_{cm} = 133$ GeV implies in the dls case a common squark mass in the range 47-61 GeV. This is consistent with the 109 GeV peak in the total dijet mass distribution reported by ALEPH. Note that R-squarks decouple at $E_{cm} \approx 133$ GeV because their photon and Z^0 contributions just cancel.

[5] L. Rolandi, Joint CERN Particle Physics Seminar on First Results from LEP 1.5, Dec. 11, 1995

Thus only L-squarks are probed at this particular energy. Furthermore, at this energy U- and D- type squarks are produced equally, if they have the same β^3 factor, making it easy to rescale from the dls case to more complicated squark mass spectra.

A $\sim$ 54.5 GeV chargino and slightly lighter squark can also account for the rate of excess dijet events and the peak in total dijet invariant mass reported by ALEPH. From a parton point of view, the chargino cascade mechanism produces 6-jet and not 4-jet events. However when the chargino-squark mass difference is small, the energy of each primary quark jet (q' in $\chi \rightarrow S_q q'$) is too low for it to be distinguished as a separate jet. Instead, the particles of the primary jets are associated to the hard jets of the event. Thus $\chi^+\chi^-$ production at this energy would lead to 4-jet events. In order to account for a peaking of the dijet total mass at 109 GeV, the chargino mass must be around 54.5 GeV.

Without tree-level gaugino masses, the masses and mixings of the charginos, and thus their production cross section, depends only on μ and $tan\beta$. The range of μ and $tan\beta$ corresponding to a given chargino mass is quite restricted: e.g., for $m(\chi^{\pm}) = 55$ [65] GeV, $tan\beta$ only ranges from 1 at the maximum allowed value of μ (62 [34] GeV, to 1.8 [1.4] when $\mu = 0$.[6] As for production of any heavy fermion pair, the threshold dependence of the cross section $\sim \beta(3-\beta^2)/2$. In order to compute the 4-jet event rate in the chargino cascade mechanism, one needs the branching fraction, b, for $\chi^{\pm} \rightarrow S_q q'$. This depends on the number and masses of sneutrinos which are lighter than the chargino. Fig. 2 shows $R_{\geq 4}$ for a 55 GeV chargino and one 53 GeV L-squark, as a function of E_{cm} for $tan\beta = 1,\ 1.4$, and 1.8 (μ is fixed by the chargino mass). b has been fixed to (0.37,0.38,0.48) for these three values of $tan\beta$, in order that $R_{\geq 4} = 2$ at 133 GeV.

It is quite plausible for b to be in this range for a squark mass in the 50-53

[6] In the MSSM such small $tan\beta$ can conflict with Higgs mass bounds, however additional scalars are expected in most models and this is is not a generic problem.

GeV range and sneutrino masses about 5 GeV lighter. Then the branching fraction for $\chi^{\pm} \rightarrow S_{\nu}\nu$, summed over snuetrinos lighter than the chargino, is $(1-b)$. At $E_{cm} = 133$ GeV, b values giving 7 excess 4-jet events imply 14-24 events with one chargino decaying to $S_q q$ and the other to $S_{\nu}\nu$, and 7-14 events with both charginos decaying to $S_{\nu}\nu$. The former produces events with 2 jets, a soft charged lepton ($E \sim m(\chi^{\pm}) - m(S_{\nu})$), and the decay products of the sneutrino; the latter produces events with two soft leptons and decay products of two sneutrinos. It should be possible to verify or exclude the chargino cascade scenario by searching for these alternate decay modes.

Now let us turn to the issue of deciding when an excess of events with $n_{jets} \geq 4$ can be attributed to direct production of $S_q S_q^*$. Three techniques are particularly useful: (i) dijets from $S_q S_q^*$ production should have equal masses, (ii) the angular distribution of jet clusters should $\sim sin^2\theta$ and $1 + cos^2\theta$ for squarks and charginos, and (iii) gluino-jet tagging.

Gauge interactions (including their SUSY-transforms involving gauginos) conserve chirality. Moreover the absence of flavor-changing neutral currents implies that gauge interactions of squarks are flavor-diagonal to high accuracy. Thus when a squark and antisquark pair is produced in e^+e^- or hadron colliders, their flavor and chirality can be taken to be the same until the sample of squarks is large enough to study rare phenomena. Furthermore, the *mixing* between eigenstates of chirality for a given flavor squark is small in this scenario[7], except for the stops. Thus the *dijets from a directly produced squark pair have equal masses when the jets are correctly paired.*. This is a crucial point. Since the various squark flavors need not be degenerate, the dijet invariant mass spectrum may be messy, with nearby overlapping peaks or enhancements. Nonetheless, a clear signal is possible since correct pair-

[7]Because trilinear squark-Higgs couplings are absent, the mixing between chirality eigenstates for squark flavor q is $\frac{\mu m_q}{M_q{}^2}$ times $cot\beta$ ($tan\beta$) for charge 2/3 (-1/3) squarks respectively.

ing of jets always leads to a vanishing *difference* of dijet invariant masses. Henceforth jets are always taken to be paired so the dijet mass difference is minimized. When the squarks are decay products of charginos they need not be identical if more than one squark is lighter than the chargino. Nonetheless the mass splitting may not be large[8].

Unfortunately, the prediction that directly produced squarks and anti-squarks are mass degenerate on an event by event basis is not a very useful tool near threshold. ALEPH modeled the distribution of dijet mass difference at $E_{cm} = 135$ GeV resulting from two 55 GeV particles each decaying to $q\bar{q}$ and found the peak in reconstructed dijet mass difference to be ~ 15 GeV fwhm. Furthermore, requiring the minimum dijet mass difference to be less than 20 GeV only reduces the number of events expected in the standard model from 8.6 to 7.1.[5] This implies that at $E_{cm} = 135$ GeV, 80% of standard model events have a dijet mass difference less than 20 GeV, when jets are paired so as to minimize the dijet mass difference and the other ALEPH cuts are satisfied. Thus while the data is consistent with equal mass squarks, this is not a very stringent test of the hypothesis.

If both direct and cascade production of squarks are important and the squark and charginos are close in mass, the event properties near chargino threshold are complicated. The particles of the soft primary quark jets in chargino decays would be associated in a more-or-less random way with the four hard jets. This would tend to broaden the dijet invariant mass distribution compared to direct squark pair production, although the average invariant mass of the dijet remains centered on the chargino mass to leading approximation. In the ALEPH anaylsis, the cut on $\min(m_i + m_j) > 10$ GeV

[8] Aside from stops, squarks produced from chargino decay are left-chiral because their gauge coupling to the wino component of the chargino is much larger than their super-Yukawa coupling to the higgsino component. The splitting between S_{UL} and S_{DL} is determined as the soft SUSY-breaking scalar mass terms respect the electroweak gauge symmetry. In obvious notation, $M_U - M_D = (cos2\beta(1 - sin^2\theta_W)M_{Z^0}^2 + m_U^2 - m_D^2)/2M_Q$, where M_Q is their average mass.

removed only 2 events from the data but 5 from the monte carlo of the SM prediction. This may be a hint of chargino cascade, because when the particles of the very soft primary quark jets are associated with the 4 hard jets, the invariant mass of the resultant jets increases.

Spin-0 particles produced in e^+e^- scattering through the spin one photon or Z^0 have a $sin^2\theta$ angular distribution. If the events with total dijet mass $\sim$ 109 GeV were due to the decay of directly produced squark pairs, taking these events alone should produce an angular distribution $\sim sin^2\theta$. The remaining events (comprised of $q\bar{q}gg$ in the absence of chargino cascade) should be produced according to the standard model and thus have a different characteristic angular dependence.

Since the total momentum of the chargino is the vector sum of the three-momentum of the squark jet and the unidentified soft quark jet, there is no direct relation between the 3-momentum attributed to the dijet and the actual chargino 3-momentum. Thus the chargino angular distribution cannot be determined near threshold. Fortunately, this situation improves as E_{cm} is increased. When the jets from chargino decay are collimated by a Lorentz boost, the ambiguity of associating particles with the correct chargino is reduced and the invariant mass and three-moemntum of the tri-jet systems should reconstruct to the chargino mass and 3-momentum, even when the three jets are not independently resolved. The angular distribution of the events in the mass peak should in this case $\sim (1 + cos^2\theta)$.

Squarks are pair produced in flavor eigenstates, to a good approximation, so that $S_qS_q^*$ events should contain two gluino jets and two jets of the same flavor, e.g., b and $\bar{b}$ or c and $\bar{c}$. There will often be additional gluon jets since with typical jet definitions (e.g., $y_{cut} = 0.01$), 40% of the hadronic Z^0 decays have ≥ 3 jet final states. The hadronization of gluino jets will nearly always produce an R^0[4] which ultimately decays to a photino which escapes. R^0-tagging could provide confirmation of the $S_qS_q^*$ origin of the excess $\geq$ 4-jet events. The R^0's decay to a photino and a small number

of pions[12]. The photino typically has a momentum transverse to the R^0 direction of $\sim 0.4-0.8$ GeV[12], depending on the relative mass of R^0 and $\tilde{\gamma}$. The average momentum fraction of an R^0 with respect to its jet, x_R, can be determined in a Monte Carlo or other model of jet fragmentation[9], or taken by analogy from, say, charm fragmentation. If the lifetime of the R^0 is short compared to the transit time of the calorimeter and its decay is two-body, the photino will have a momentum along the jet ranging up to $x_R \frac{M_{sq}}{2}$. On the other hand, if the R^0 lifetime is long enough that it loses its kinetic energy in the calorimeter before decaying, the momentum along the jet axis carried away by the photino will be nearly imperceptible.

As can be seen from Fig. 2, with improved statistics and higher energy LEP measurement of $R_{\geq 4}$ will provide a powerful tool to support or exclude the hypothesis that squarks are being produced. Mapping the $\geq$ 4-jet energy dependence should allow cascade and direct production to be distinguished. If charginos are being produced, the threshold dependence of $R_{\geq 4}$ allows their mass to be found. If a chargino with mass less than m_W is eventually excluded, SUSY-breaking which does not produce tree level gaugino masses will be ruled out unless μ is much larger than has been considered plausible up to now[2]. If on the other hand a chargino but not squarks are found below the W, the search for squarks in $\geq$ 4-jet events should be pursued at higher energy. The range of LEP can be extended somewhat by allowing one member of the squark pair to be off-shell. Then only one pair of jets will reconstruct to a definite invariant mass and the signal will be less clear.

At a hadron collider the background is more severe, but the signal-to-noise improves with increasing squark mass. Chargino cascade is not a significant source of squarks in a hadron collision, so with good resolution a peak should be found in the mass difference of dijets, with the flavor of two of the jets being the same. At a cost of a factor of 100 in rate, one could trigger on

[9]The $x_{\tilde{g}}$ distribution and invariant mass of gluino jets was estimated in [13].

events in which a squark decays to quark and photino. This produces events with missing energy, one dijet and one or more additional jets. These events would contain, ignoring mass differences, equal numbers of L- and R-squarks with a 4-1 enhancement of events with U-squarks. The mass-splitting between L- and R-squarks of the same flavor is not determined by $tan\beta$ as it is within an SU(2) doublet, since squarks in different SU(2)xU(1) representations can have different soft SUSY-breaking masses. If at low energy the SUSY-breaking contribution to scalar masses is universal, the $S_{uL}-S_{uR}$ mass splitting is $cos2\beta(\frac{1}{2}-\frac{4}{3}sin^2\theta_W)\frac{m_Z^2}{2M}$. This is less than 2 GeV, for $m(\chi^{\pm} \geq 70$ GeV and $M_sq \geq 100$ GeV. In this case events with missing energy and ≥ 3 jets would show a peaking in dijet mass, even though the squarks are not precisely degenerate.

In e^-p collisions a produced squark is 4-8 times as likely to be a u-squark as a d-squark depending on the x regime of the collision: a factor of 4 from the quark charge-squared and a factor of $1-2$ from the relative probability that the initial parton is a u versus d quark. Ignoring therefore the production of d-squarks, the probabilitiy that squark production leads to a prompt photino is 4%. Half the time the photino is associated with a dijet which reconstructs to the u-squark mass; the other half of the time the two jets accompanying it have no particular relation as one came from the decaying squark and the other was the primary gluino associated with the squark production.

To recapitulate, the signatures of squarks and charginos have been discussed when SUSY breaking does not produce tree-level gaugino masses or scalar trilinear couplings. In this case a chargino must be lighter than the W and the gluino is light and hadronizes. If a L-squark is lighter than the chargino, the primary decay of the chargino is to squark + quark and the usual signatures relying on the decay $\chi^{\pm} \rightarrow \chi^0 f \bar{f}'$ are diminished in utility. 99% of pair-produced squarks produce events with four or more jets and little missing energy. Emphasis was placed on features of events with four or

more jets which are characteristic of $S_q S_q^*$ production or (possibly relevant at LEP) of chargino production and decay to squarks. The energy dependence of events with 4 or more jets is a powerful tool to establish the existance of a signal and to discriminate between cascade and direct squark production. Properties of gluino-containing jets which could be helpful in discriminating them from quark or gluon jets are discussed.

The excess of 4-jet events reported recently by ALEPH[5], if confirmed by other experiments and higher statistics, could be circumstantial evidence that at least one L-squark has a mass $\lesssim 55$ GeV and decays to quark and hadronizing gluino. The number of 4-jet events in their total-dijet-mass peak at 109 GeV is consistent with direct production of two generations of L-squarks with mass 55 GeV, or production of a 55 GeV chargino which decays to a squark and quark. In the latter case, events with a pair of jets and decay products of sneutrinos are expected. Higher energy running can easily exclude or confirm these possibilities. Careful study of 4-jet events should be a standard part of squark search techniques until a light, hadronizing gluino has been excluded.

Acknowledgements: I have benefited from discussing these matters with L. Clavelli, J. Conway, P. Janot, S. Lammel and R. Rattazzi.

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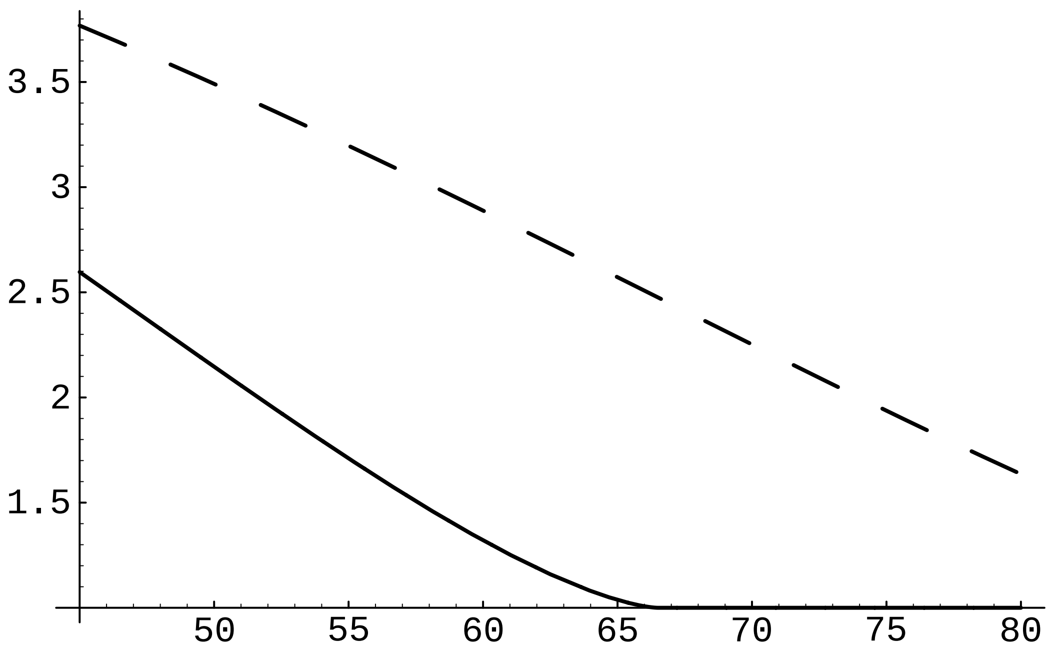

Figure 1: $R_{\geq 4}$ for degenerate $u,\ d,\ s,\ c$ squarks as a function of their mass in GeV. Solid (dashed) curve is for $E_{cm} = 133$ (190) GeV.

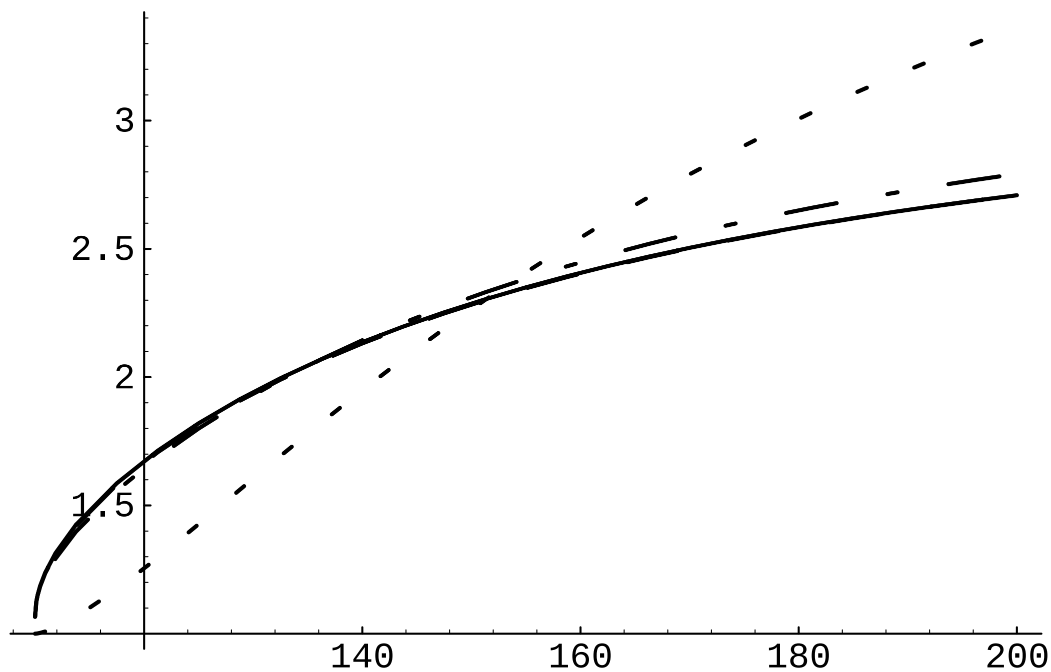

Figure 2: $R_{\geq 4}$ as a function of E_{cm} for a 55 GeV chargino with $tan\beta = 1,\ 1.4,$ and 1.8 (solid, dashed and dash-dotted curves) and for 55 GeV dlsquarks (dotted curve).